A CLOSER LOOK AT SALT, FAULTS, AND GAS IN THE NORTHWESTERN GULF OF MEXICO WITH 2-D MULTICHANNEL SEISMIC DATA

A Thesis

by

LESLIE ANN NEMAZI

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2010

Major Subject: Oceanography

A Closer Look at Salt, Faults, and Gas in the Northwestern Gulf of Mexico with 2-D

Multichannel Seismic Data

A CLOSER LOOK AT SALT, FAULTS, AND GAS IN THE NORTHWESTERN GULF OF MEXICO WITH 2-D MULTICHANNEL SEISMIC DATA

A Thesis

by

LESLIE ANN NEMAZI

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Chair of Committee,	William Sager
Committee Members,	William Bryant
	Richard Gibson
	Adam Klaus
Head of Department,	Piers Chapman

May 2010

Major Subject: Oceanography

ABSTRACT

A Closer Look at Salt, Faults, and Gas in the Northwestern Gulf of Mexico with 2-D Multichannel Seismic Data. (May 2010)

Leslie Ann Nemazi, B.S., The University of Michigan

Chair of Advisory Committee: Dr. William Sager

The sedimentary wedge of the northern Gulf of Mexico is extensively deformed and faulted by salt tectonics. Industry 2-D multichannel seismic data covering a large area (33,800 km^2) of the lower Texas continental slope [96°40'- 93°40'W; 27°10N - 26°N] were examined to evaluate the interplay of salt, faults and gas. Seismic interpretation revealed the study area has two different styles of faulting and two different types of salt bodies that vary east to west. The eastern region of the study area has a thin sedimentary section and a massive, nearly continuous salt sheet characterized by minibasins and local salt highs. Faulting in this area appears to be the result of salt tectonism. The western region of the study area has a thick sedimentary wedge, and a few isolated salt diapirs. Long, linear faults are parallel to slope and imply some degree of gravitation sliding. The difference in faulting styles and salt bodies can be attributed to different depositional environments, different styles and amounts of sediment loading and different amounts of salt initially deposited.

While there is a widespread occurrence of gas throughout the study area, little evidence of continuous bottom simulating reflectors (BSRs), a widely accepted geophysical indicator of gas hydrate, has been found. The gas hydrate stability zone (GHSZ) was modeled to provide information on the thickness and variability of the stability zone, and provide a baseline in a search for BSRs. The dataset was analyzed for multiple seismic expressions of BSRs, however only a few small and isolated examples were found. Potential fluid escape structures were seen in the seismic data. Despite the great number of potential features found in the seismic data only seven active seeps were found in a seep study by I. R. MacDonald. Seeps were seen in far less abundance than the number of seeps found offshore Louisiana. This may imply a lack of source offshore Texas.

ACKNOWLEDGEMENTS

I would like to thank my adviser Dr. W. Sager for his support, and Dr. W. Bryant, Dr. R. Gibson, Dr. A. Klaus, and Dr. M. Lyle, for their help throughout the course of my research. I would also like to thank TGS-NOPEC Geophysical Company L.P. for providing the seismic data.

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

The Gulf of Mexico is an unique small ocean basin. While the overall structure of the basin is fairly simple, the overlying sediment and salt create a complex architecture. The northern Gulf of Mexico, in particular the Texas slope, has been studied by both industry and academia; however, many details remain unclear. We know that there is a thick, extensive salt layer that has greatly deformed the continental margin sedimentary wedge (Worrall and Snelson, 1989), but the details of deformation and structures in many areas are unclear. The goal of this project was to use a grid of industry multichannel seismic data to get a better understanding of the subsurface salt structures of the Texas Continental slope and how they affect surface morphology, as well their implications for tectonic processes, and to evaluate the potential geophysical indicators of gas and gas hydrate, which are both known to occur in the area (MacDonald et al., 1994, Frye, 2008).

Lack of geologic detail extends from the surface, where high-resolution bathymetric data have not been published, to below the seafloor, where the relationship between salt, sediments, faults and gas is still mostly undocumented. Much has yet to be learned about the salt and faults in the area. The distribution and the styles of faulting, as well as the distribution and the morphology of the salt, can be better understood with seismic analysis.

This thesis follows the style of *Marine and Petroleum Geology.*

It is commonly accepted that gas hydrate is present in the northern Gulf of Mexico, and has been photographed outcropping at the seafloor (MacDonald et al., 1994). However in terms of geophysical evidence, very few examples of the classic indicator of gas hydrate, the bottom-simulating reflector (BSR), have been found. A BSR forms at the interface between sediment that contains gas hydrate and sediment that contains free gas and water, as the gas hydrate bearing sediment traps free gas at its base (Kvenvolden, 1993) and the trapped gas makes a large acoustic impedance contrast that causes a strong reflection. BSRs mark the base of the gas hydrate stability zone (BHSZ), as hydrate only forms and remains stable above the BHSZ (Kvenvolden, 1993). Recent research suggests that the classic picture of the BSR is oversimplified and applies best to relatively homogeneous sediments (McConnell and Kendall, 2003). In heterogeneous sedimentary sequences, such as those of the Gulf of Mexico, the BHSZ may be expressed seismically in various ways such as in a continuous, segmented or high relief BSR. Adapting the BSR interpretations of McConnell and Kendall, (2003), and Shedd et al. (2009), the seismic data in this study can be utilized to try to find seismic indicators of gas hydrate.

2. BACKGROUND

2.1 Gulf of Mexico Evolution/Tectonics

The structure of the Gulf of Mexico is the result of multiple rifting episodes, crustal extension, continuing sedimentation, and salt emplacement and mobilization. The initial period of rifting took place in the Late Triassic to Early Jurassic (Sawyer et al., 1991). This phase of early rifting created half-grabens and rift basins, bounded by listric normal faults, which were filled with non-marine sediments and volcanics (Sawyer et al., 1991). Transitional crust was created as the continental crust was thinned due to extension (Salvador, 1991).

The second period of rifting occurred in the Middle to Late Jurassic, during which the crust was additionally thinned by extension (Salvador, 1991). This was the main phase of crustal attenuation, and the basement highs and lows that we see today in the modern Gulf of Mexico were formed (Sawyer et al., 1991). The Louann Salt was deposited during the Mid-Jurassic over the thinned continental, or transitional, crust (Sawyer et al., 1991). Salt accumulations are thickest over the grabens that formed as a result of rifting, and thinnest by the landward edge of the basin over structural highs (Salvador, 1991). Where salt deposited in an actively subsiding basin, a thick section was accumulated, due to the increasing amount of accommodation space (Watkins, 1995). Thin salt accumulations are found over structural highs where there was less room for deposition (Salvador, 1991).

In the late Jurassic there was a major marine transgression (Worrall and Snelson, 1989). Sediment, mainly marine, began depositing over the salt layer, marking the beginning of sediment loading. In addition, oceanic crust was formed in the deep Gulf of Mexico and thus split the salt into two sections, with the Louann salt province in the north. A short period of seafloor spreading began along a weak zone in the thin transitional crust, probably lasting for only 5-10 m.y. (Bird et al., 2005). Subsidence began as the newly formed crust began to cool. The seafloor spreading was the last major plate tectonic event in the evolution of the Gulf of Mexico.

Subsequent deformation of the Gulf of Mexico is the result of crustal cooling, sediment deposition and loading, gravitational sliding, subsidence, and salt tectonics. The mid-Jurassic salt began to mobilize as sediment accumulated atop the salt layer creating overburden, while gravity began to pull the salt down slope (Nelson, 1991). Salt deformation continues through the present.

Subsidence rates were highest during the Early Cretaceous (Sawyer et al., 1991). With continuing sedimentation the oceanic crust subsided to form the deepest part of the Gulf of Mexico, while the continental and transitional crust subsided to form the shelf and slope of the basin. In addition, there was an sea level high stand in the Mid- and Upper Cretaceous, which increased sediment input and contributed to subsidence (Sohl et al., 1991).

The continuing sedimentation in the Gulf of Mexico has generated a great amount of hydrocarbon. As organic materials are deposited and buried to great depths, they are thermally altered and 'cooked' into hydrocarbons. Salt effects the relative temperature of the sediment, increasing the local temperature above salt bodies, and decreasing the local temperature below salt bodies. The hydrocarbons, in the form of gas and oil, are either trapped along a salt dome or in a stratigraphic trap, or migrate and are expelled along faults (Sassen et al., 1994). Salt also drives salt tectonics, thus influencing the generation and transportation of hydrocarbons.

2.2 Gas Hydrates

Gas hydrate is an ice-like crystalline substance, found in permafrost environments or within ocean sediments, that traps certain molecules of gas within a cage of water molecules (Kvenvolden, 1993). While several different gases can be trapped in the hydrate, methane is the most common on continental margins (Hardage and Roberts, 2006). Evidence of potential hydrate occurrence is often inferred from seismic data where a BSR occurs (Shipley et al, 1978). A BSR marks the base of the gas hydrate stability zone (GHSZ), a zone where both temperature and pressure are in the appropriate ranges for hydrate to form and remain stable. The base of the gas hydrate stability zone (bGHSZ) is the intersection between the geothermal gradient and the hydrate stability curve. The GHSZ extends from the bGHSZ to the seafloor at ocean depths where gas hydrate is stable. The bGHSZ can be approximated using:

for 100% CH_4:

$$[f(B)= - (-9.6 \times Ln(B) + 88.4) \times C/1000 - 295.1 \times B^{-0.6} + 8.9 \times Ln(C + B) - 50.1]$$

for 95.9% CH_4:

$$[f(B)= - (-9.6 \times Ln(B) + 88.4) \times C/1000 - 295.1 \times B^{-0.6} + 7.1 \times Ln(C + B) - 33.9]$$

for 90.4% CH_4:

$$[f(B)= - (-9.6 \times Ln(B) + 88.4) \times C/1000 - 295.1 \times B^{-0.6} + 6.7 \times Ln(C + B) - 27.6]$$

where B is water depth (mbsl), and C is the thickness of the GHSZ in meters (Milkov and Sassen, 2001). These equations are derived from bottom water temperature, geothermal gradient, and the temperature of gas hydrate stability for different concentrations of methane:

$$T_w = 295.1 \times B^{-0.6}$$

$$G = - 9.6 \times Ln(B) + 88.4$$

$$T_{st\_100} = 8.9 \times Ln(D) - 50.1$$

$$T_{st\_95.9} = 7.1 \times Ln(D) - 33.9$$

$$T_{st\_90.4} = 6.7 \times Ln(D) - 27.6$$

where T_w is bottom water temperature (°C), B is water depth (mbsl), G is geothermal gradient (°C/km), T_{st} is the temperature of gas hydrate stability (°C) at depth D (m). The model provides a good baseline estimate of the GHSZ, however it does not take into account localized or episodic changes in the fluid temperature, pore water salinity, gas composition, and thermal effect of salt, which may alter the thickness of the GHSZ (Milkov and Sassen, 2001).

Outside of the hydrate stability zone, hydrates will not usually form and existing hydrates will dissociate as the conditions do not support hydrate stability (Hardage and Roberts, 2006). Even though gas hydrate has been documented in the northwestern Gulf of Mexico, there has been little published geophysical evidence of widespread BSRs.

A highly irregular base of the BHSZ may prevent a continuous and recognizable BSR from forming (Cooper and Hart, 2003). Salt bodies have a different thermal conductivity than surrounding sediment and can cause a local rise in temperature (Ruppel et al., 2005). Salt bodies, along with warm migrating fluids, may be responsible for an irregular bGHSZ.

Recent work has suggested several alternative seismic characters that may indicate the presence of gas hydrate or the base of the gas hydrate stability zone. Shedd et al., (2009) described three different seismic expressions of the base of the gas hydrate stability zone. They define a "continuous BSR," a "segmented BSR," and a "high-relief BSR." Combinations of all three types of BSR's, or more than one end-member, are also possible (Shedd et al., 2009). The "continuous BSR" is the classic BSR that mimics the geometry of the seafloor, has a clear crosscutting relationship to surrounding strata, and the opposite seismic polarity with respect to the seafloor (Shedd et al., 2009). In the northern Gulf of Mexico this type of BSR is found within minibasins, but more commonly over shallow diapiric salt structures (Shedd et al., 2009). A "segmented BSR" is more difficult to recognize because it is discontinuous. It consists of separate 'bright spots,' that when connected are similar in shape to the seafloor (McConnell and Kendall, 2003, Shedd et al., 2009) and at the appropriate depth for the bGHSZ. The bright spots occur in layers with high porosity. BSRs do not form in fine grained sediments, which may explain the lack of BSRs in the northern Gulf of Mexico. Segmented BSRs were found most often on the flanks and centers of minibasins in the northern Gulf of Mexico (Shedd et al., 2009). The "high-relief BSR's" were found to be the least common form of BSR. They are found near the edges of salt bodies and in areas with highly variable heat flow due to migrating fluids and or gas (Shedd et al., 2009). The high-relief BSR's are not bottom simulating and are found close to the seafloor in a plume or cone shape, hence the name 'high-relief.' While the addition of BSR definitions increases the total number of BSR recognized occurrences in the Gulf of Mexico, occurrences of BSR nevertheless appear spotty.

3. METHODS/DATA

Industry 2-D multichannel seismic data from TGS-NOPEC, Inc. were the basis of this study. These data cover a large area (33,800 km^2) of the lower Texas continental slope [96°40'W - 93°40'W; 27°10N - 26°N (see Fig. 1). The study area consists of two OCS lease block areas, Port Isabel and Alaminos Canyon. The area includes the Sigsbee Escarpment, Alaminos Canyon and the northwestern part of the Perdido Fold Belt (the structure of which is not part of this study). The seismic record extends from 0 to 6.7 seconds, and a sample interval of 4 milliseconds. The seismic lines have an average grid spacing of ~3.3 km and a shotpoint interval of 37.5 meters. Streamer lengths of 6000 and 8000 meters were used with nominal folds of 80 to 106. Spherical divergence, deconvolution and normal moveout correction were components of the processing sequence in conjunction with DMO velocity analysis every kilometer and an 80 fold DMO stack. Finite difference migration and time varying and FK filters were also used.

The seismic data analysis program *Kingdom Suite* by Seismic Micro Technology was used for the seismic interpretation. The top of salt (TOS) was picked as a horizon and gridded across the study area. Salt was identified by a strong acoustic impedance contrast overlying a chaotic zone lacking coherent seismic reflections. Structural deformation in the overlying sediments provided further evidence that the strong acoustic impedance contrast belonged to the TOS. Faults were identified by bed terminations and offset in the strata and seafloor. An isopach map detailing the thickness of sediment above the layer of salt was made in Kingdom Suite using gridded horizons of the seafloor and the TOS. Gas indicators include bright spots and areas of low reflectivity, and were mapped as horizons. Bright spots, and sequences of discontinuous bright spots, with crosscutting relationships with the surrounding strata were mapped as BSRs. A model bGHSZ was calculated in MatLab and imported into Kingdom Suite, based on the equations in Milkov and Sassen (2001). As hydrates are not always composed of 100% methane, the bGHSZ was calculated for three different gas concentrations. The three bGHSZ's calculated were 100%, 95.9% and 90.4% CH_4, with 100% CH_4 giving the thinnest GHSZ and 90.4% CH_4 giving the thickest bGHSZ.

4. RESULTS

4.1 Salt

While some topographic features of the buried salt are reflected by seafloor bathymetry, most of the salt is buried under a layer of sediment and the salt topography is hidden (see Fig. 2). The TOS was mapped across the study area. It revealed rugged topography and showed two regions of differing salt morphology.

The western most part of the study area, in the Port Isabel lease blocks, differs from the eastern part of the study area. In the western region, the salt bodies are smaller, more isolated and less abundant. Diapirs are common, and are found isolated and surrounded by sediment. The salt is not present in a continuous sheet, and most of the area is either devoid of salt or the salt occurs below 6.7 seconds of two-way travel time (twtt), which is the bottom of the data set. This is seen clearly in Fig. 2.

The salt in the eastern region of the study area is more widespread, massive, and continuous. The surface topography is rugged and many highs and lows can be seen in the TOS. There are a few large basins, as well as some local highs. The Sigsbee Escarpment is clearly defined in the eastern region. It marks the basinward limit of the salt, except for a salt plug found located in the center of Alaminos Canyon (see Fig. 2).

The thickness of salt in this data set could not be determined because the base of salt (BOS) could not be mapped except in a few spots where the salt is thin. The BOS is either not properly imaged or it occurs below the bottom depth of the data. Below the TOS, which is easily identified, reflections are chaotic and much of noise is present.

Even if the salt is thin enough so the BOS would be present in the seismic section, it may be drowned out by noise.

An isopach map of the sediment above the salt was created for the study area (Fig. 3). It shows the thickness of the sediment between the TOS and the seafloor, and relates the seafloor topography to the TOS. It also gives quantitative information on basin infill. Sediment thickness is much greater in the western region of the study area from approximately 96°40'W to 96°10'W. The western region of the study area is closer to a sediment source, the Rio Grande and Colorado Rivers, and as a result more sediment accumulates (Galloway et al., 2000). The rest of the study area [96°10'W to 93°40'W], has a thinner sediment section as it is farther from the Rio Grande River and other contributing Texas rivers (Coleman et al., 1989). Local thickness variations are due to minibasins and salt highs. Sediment accumulates in minibasins, and thins over salt highs. Erosion, faulting and slope failure are some of the processes that thin the sediment section. The area south of the Sigsbee Escarpment does not receive much sediment input as it is both deeper that the rest of the area and farthest from a source.

4.2 Fault Distribution and Styles

Examination of the seismic data revealed two distinct styles of faulting within the study area. Similar to the salt morphology, the faulting styles vary east to west (see Figs. 4 and 5). In the western portion of the study area, the faults are primarily long, curvi-linear normal faults. The wide grid spacing of the seismic survey makes it impossible to correlate most of the faults definitively from one seismic line to other adjacent lines.

This is unfortunate, as it would have enabled us to map and determine the orientation of the faults in the western region. While the exact geometry of the faults is unclear, a regional trend is observed. The western region of the study area, with the small isolated salt bodies, has a very thick sedimentary section compared to the eastern region. The faults extend throughout most of the seismic section, with some reaching to the seafloor. Fault displacement is usually not obvious at the seafloor.

The faulting in the eastern portion of the study area is much more localized than the regional style of faulting to the west. Faults are located above the quasi-continuous salt body, and lie within a shallower sedimentary section. These shallow faults sole into the underlying salt body. Faulting appears largely due to salt tectonics. Both normal and reverse faults are seen, providing evidence of repeated salt withdrawal and intrusion. Some faults are reactivated in the opposite direction after salt remobilization. Offset is common at the seafloor, indicating active salt tectonism (see Fig. 4).

4.3 Seismic Indicators of Gas and Gas Hydrate

There is much evidence in the seismic data of widespread shallow gas throughout the study area. The acoustic impedance contrast between water saturated sediment, and sediment containing gas is represented in a variety of ways. 'Bright spots', 'ringing', velocity pull down and areas of acoustic 'wipeout' are all seismic indicators of near surface free gas (Anderson and Bryant, 1990). Many small, localized 'bright spots', the result of high acoustic reflectivity, are seen in the data set. 'Bright spots' appear as unusually strong reflectors compared with the surrounding strata. 'Ringing' is seen in some shallow water areas and velocity pull down is sometimes present at the edge of a gassy zone (Anderson and Bryant, 1990). The most common seismic indicators of free gas in this data set are acoustic wipeouts and zones of acoustic turbidity. Gas indicators were seen throughout the seismic data set as "hazy" layers or areas with low reflectivity and faint or absent layering. Hazy layers were found predominantly above salt bodies and relatively near the surface across the entire study area (see Figs. 5 and 6). Total wipeout occurs in some isolated spots. The variable magnitude of acoustic wipeout is likely due to varying amounts of gas, with the greater wipeout caused by greater amount of gas. While it could be argued the that wipeout or seismic blanking is the result of gas hydrate, the same blanking effect is seen in areas too shallow to support hydrate. Surface features such as pock marks, collapse structures, mud mounds and gas chimneys usually provide additional support that seismic blanking indicates the presence of gas (Reilly et al., 1996; Anderson and Bryant, 1990). These surface features are often seen in the eastern portion of the study area above areas of seismic blanking.

In my search for BSRs, no traditional continuous BSRs were found. The alternatives defined by Shedd et al (2009) were taken into account when examining the seismic data in this study, and examples of this style were found. Many potential indicators of gas hydrate were found using the new definitions, ranging in size from 0.7 km to 14 km. "Segmented" and "continuous" BSRs were found, although no "high-relief" BSRs were seen (see Figs. 6 and 7).

Although the scope of the search was broadened by including the new BSR definitions, no widespread or largely continuous BSR's were found. The potential BSR's that were found were isolated and small, suggesting that gas hydrates are present, just not in great abundance. The grid spacing of the survey (~3.3km) often prevented detailed mapping of the potential BSRs that were found, as the lateral extent of the potential BSRs could not be determined. For example, using a 3-D seismic survey would allow each BSR to be mapped in every direction and provide complete coverage of the area (see Fig. 8).

4.4 Gas Seeps

Seven seep locations (I. R. MacDonald, personal communication, 2009) compared to seep structures seen in the seismic data (see Fig. 8). Seismic data near these locations were examined for evidence of fluid escape features, such as tensional faults above salt, surficial mud mounds and gas chimneys (Reilly et al., 1996). Analysis of the seismic data showed featured consistent with potential fluid expulsion over the majority of the area, and over 100 potential sites were identified in the seismic data. Because the seismic line spacing (3.3 km) is larger than many fluid expulsion features (< 1 km), it is likely that many more exist in the area, but were not identified in the seismic data set. Six of the seven seep sites corresponded with areas of potential fluid expulsion in the seismic data, while one site showed no correlation. Lack of correlation for that one site may be due to the seismic line spacing. The six sites that showed correlation with expulsion features in the seismic data may be actively seeping from the fluid expulsion structure found in the seismic data or a structure nearby in between seismic lines.

5. DISCUSSION

5.1 Salt

The northwestern Gulf of Mexico has a rugged topography, largely due to the mobility of the Louann salt that was deposited in the mid-Jurassic (Salvador, 1991). Bathymetric highs are the result of salt diapirism and uplift, and bathymetric lows are the result of salt withdrawal. These seafloor expressions of the underlying salt mechanics manifest into minibasins that can be seen in the bathymetry and seismic data (Bryant et al., 1990).

The difference in the two types of salt morphology noted in the study area can be attributed to the fact that salt is a mobile substrate, and there have been multiple mobilizations of the salt since its emplacement in the mid-Jurassic. A variable initial salt thickness and sediment influx over time is also a factor. When salt was originally deposited in the Gulf of Mexico, it was thickest in the center of the basin due to greater accomodation space (Worrall and Snelson, 1989) and thinnest at the landward edges of the basin. Over time, the terrigenous sediment influx along the border of the Gulf of Mexico has caused the salt to shift basinward. Sediment is deposited and accumulates over the salt until the overburden pressure gets too high and the salt moves out, or there is a slope failure and a resulting sediment flow.

The depositional environment controls the influx of sediment to the Gulf of Mexico. The Texas coast has a barrier island depositional system which supplies a steady stream of sediment to the Gulf evenly loading the salt (Worrall and Snelson, 1989). Due to the sediment loading the salt is either deeply buried or it mobilizes and moves out. In contrast, the drainage pattern of the deltaic Louisiana coast is constantly changing, resulting in uneven sediment loading of the salt (Worrall and Snelson, 1989) and a thicker, more continuous salt sheet.

In the western portion of the study area, the salt bodies are isolated diapirs surrounded by sediment. That area is closest to the barrier island depositional setting which may explain the lack of continuous shallow salt. A steady influx of sediment creates a large overburden pressure for the salt, forcing it deeper, below the depths of the seismic survey, or cause it to move basinward, where we see a more continuous shallow salt section. This area was also at the edge of initial salt deposition and a contained thinner salt than the eastern portion of the study area.

In the eastern portion of the study area, the salt is fairly continuous and massive. This area is not directly basinward of a barrier island depositional setting, and is influenced by alluvial and deltaic systems (Worrall and Snelson, 1989). The less concentrated sediment influx does not form large enough overburden pressures for salt to evacuate, which creates the continuous salt seen in the eastern region. In addition more salt was originally deposited in this area due to more accommodation space. I think the different morphologies are due to different paleogeographies, amount of initial salt deposition, increased sedimentation in the western region, multiple salt mobilizations and basin ward salt movement throughout time.

5.2 Fault Distribution and Styles

The style of faulting seen in the western portion of the study area is indicative of gravitational extension (Worrall and Snelson, 1989). The faulting in the western region is just east of the Lunker, Clemente-Tomas, Corsair and Wanda fault systems which are long, listric basinward dipping growth faults (Worrall and Snelson, 1989). The western faults seen in the seismic data are similar in style to the regional fault systems and are mainly caused by subsidence of sediment and gravitational sliding. The faults are very similar to the "Texas faults" from Worrall and Snelson, 1989.

The faults seen in the rest of the study area are the result of salt tectonics, and similar to the "Louisiana faults" from Worrall and Snelson, 1989. Multiple salt mobilizations and continuing sedimentation are two key driving forces of the tectonism in the region. The faults are much shorter than the deeply soled faults to the west, because the salt is much shallower and more continuous in the eastern region. The faults are constrained to the thin sediment section above the salt, whereas in the western region the sediment section is much thicker which allows the faults to extend deeper. The different driving forces behind the faulting, result in different styles of faulting. Sediment instability in the west results in gravitational extension, while salt tectonism in the east is driven by salt instability. Because the western faults area caused by a large regional sediment load, they are less local and complex. The eastern faults are caused by local sources, salt movement, and are local and often complex.

5.3 Hydrate Potential

Gas was seen throughout the seismic data. Despite the widespread occurrence of gas, few BSRs were found. Therefore something must be prohibiting the formation of gas hydrate (cause of BSR), as gas hydrate has been found outcropping at the seafloor offshore Louisiana (MacDonald et al., 1994).

The bGHSZ was modeled to provide a baseline when looking for BSR's, and to examine the GHSZ to provide insight to help explain the lack of BSR's. The equations used were from Milkov and Sassen (2001). While they do not account for every factor that would affect the thickness or stability of the hydrate stability zone, it does provide a good maximum thickness estimate in the absence of enhanced heat flow caused by salt or fluid flow. In reality the hydrate stability zone would be much thinner due to the thermal perturbations caused by the large volume of shallow salt. In addition to salt, many factors could cause temperature anomalies such as warm migrating fluids, and warm eddies from the Loop Current in the Gulf of Mexico (Hardage and Roberts, 2006).

Milkov and Sassen's equations predict that a widespread GHSZ is present. While the high thermal conductivity of salt would thin the stability zone it would not cause it to disappear entirely over a broad area. Heat flow that high would be limited in area (Ruppel et al., 2005). There must be other factors limiting BSR formation. Other factors that would affect BSR formation could include permeability and gas concentration. If the sediment layers above the salt, in the calculated GHSZ, have a low permeability there would not be enough room for hydrate to form in the pore space. While the seismic data indicates gas is present almost everywhere, the actual concentration of each accumulation may be low. There is a varying degree of acoustic wipeout in the study area. Complete wipeout is seen less frequently than moderate wipeout, which may imply we are seeing hundreds of low concentration gas deposits or accumulations.

5.4 Gas Seeps

The same observations apply to gas seeps. Why did we find so many fluid and gas expulsion structures compared to the number of actual seeps in the previous study? In the study by MacDonald et al, seeps were identified from the intersection of surface oil slicks. In this study only seismic data were used. The difference in detection methods may account for some of the contrasting results. The seismic data revealed numerous structures that could vent fluids and gas to the surface. While the structures were found in great abundance, there is no way to tell if they are actively venting. The MacDonald study highlighted active seeps. The discrepancy between number of structures and number of active seeps may indicate that the salt layer acts as a seal and/or that there is not much oil and gas present to vent to the surface. There are a lot of active seeps offshore Louisiana despite the thick salt sheet. Why are there fewer seeps offshore Texas? Salt is present in both locations, and may be thicker offshore Louisiana [(Worrall and Snelson, 1989), (Watkins et al., 1996)]. In addition, the structures and sediment sequences are similar offshore Texas and Louisiana. Therefore something else must be creating the difference in number of active seeps. The discrepancy in the number of seeps between offshore Texas and Louisiana may be attributed to the hydrocarbon source. The source could be different, constrained, or limited offshore Texas.

6. CONCLUSIONS

The study area can be divided into a western and eastern region. Both style of faulting, and salt morphology differ in each region. The salt morphologies differ as a result of the depositional environments and the paleogeography of the coast. The western region of the study area, is a barrier island system that loads a large volume of sediment over the salt layer, effectively deeply burying the salt or causing it to evacuate the area and move basinward (Worrall and Snelson, 1989). The seismic data shows isolated diapirs surrounded by a thick sediment section.

The eastern region of the study area is influenced by an alluvial and deltaic environment. It is not as close to a sediment source as it is farther offshore than the western region. The sediment is dispersed through the ephemeral drainage patterns of a deltaic system. The uneven loading of sediment on the salt creates a minibasins and interbasin salt domes (Worrall and Snelson, 1989). The rugged bathymetry is the result of the complicated relationship between salt and sediment.

The style of faulting is directly related to the salt, and in turn the depositional environment. The western region has long, linear normal faults throughout a thick sedimentary wedge. Faulting in the eastern region is confined to the thin section above the salt, and the result of salt uplift and uneven sediment distribution and loading.

Gas is seen throughout the seismic data, especially above salt bodies near potential fluid escape structures. A seep study by I. R. MacDonald identified seven active seeps by the intersection of surface oil slicks. The seep locations were correlated with the seismic data. Potential fluid escape features were found in the seismic data for six of the seven sites. Far more than seven structures were seen in the seismic data, implying that a lot of seep sites are older and currently inactive, and that a source may be limited.

The bGHSZ was modeled to evaluate the GHSZ and examine the BSR occurrence. The data were evaluated for multiple definitions of BSRs, including "high-relief," "segmented," and "continuous." Despite a widespread occurrence of gas, no widespread BSRs were found. Lots of small, isolated potential "segmented" and "continuous" BSRs were found. No "high-relief" BSRs were found.

REFERENCES

Anderson, A.L., Bryant, W.R., 1990. Gassy sediment occurrence and properties: Northern Gulf of Mexico. Geo-Marine Letters 10, 209-220.

Bird, D.E., Burke, K., Hall, S.A., Casey, J.F., 2005. Gulf of Mexico tectonic history: Hotspot tracks, crustal boundaries, and early salt distribution. AAPG Bulletin 89.3, 311-328.

Bryant, W.R., Bryant, J.R., Feeley, M.H., Simmons, G.R., 1990. Physiographic and bathymetric characteristics of the Continental Slope, Northwest Gulf of Mexico. Geo-Marine Letters 10, 182-199.

Coleman, J. M., Roberts, H. H., Bryant, W. R., 1991. Late Quaternary Sedimentation. In: Salvador, A., (Ed.), The Gulf of Mexico Basin. The Geology of North America vol. J, The Geological Society of America. Boulder, Colorado, pp. 325-351.

Cooper, A.K., Hart, P.E., 2003. High-resolution seismic-reflection investigation of the northern Gulf of Mexico gas-hydrate-stability zone. Marine and Petroleum Geology 19, 1275-293.

Frye, M. (Ed.), 2008. Preliminary evaluation of in-place gas hydrate resources: Gulf of Mexico outer continental shelf. OCS Report MMS 2008-004, Minerals Management Service, New Orleans, Louisiana, 122 pp.

Galloway, W.E., Bebout, D.G., Fisher, W.L., Dunlap, J.B., Cabrera-Castro, R., Lugo-Rivera, J.E., Scott, T.M., 1991. Cenozoic. In: Salvador, A., (Ed.), The Gulf of Mexico Basin. The Geology of North America vol. J, The Geological Society of America. Boulder, Colorado, pp. 245-324.

Galloway, W.E., Ganey-Curry, P.E., Li, X., Buffler, R.T., 2000. Cenozoic depositional history of the Gulf of Mexico basin. AAPG Bulletin 84.11, 1743-774.

Hardage, B.A., Roberts, H.H., 2006. Gas Hydrate in the Gulf of Mexico: What and where is the seismic target? The Leading Edge May, 566-71.

Holbrook, W.S., Hoskins, H., Wood, W.T., Stephen, R.A., Lizarralde, D., Leg 164 Science Party, 1996. Methane hydrate and free gas on the Blake Ridge from vertical seismic profiling. Science 273, 1840-1843

Kvenvolden, K.A., 1993. Gas Hydrates-geological perspective and global change. Review of Geophysics 3, 173-87.

MacDonald, I.R., Guinasso, N.L., Sassen, R., Brooks, J.M., Lee, L., Scott, K.T., 1994. Gas hydrate that breaches the sea floor on the continental slope of the Gulf of Mexico. Geology 22, 699-702.

MacDonald, I.R., Sager, W.W., Peccini, M.B., 2003. Gas hydrate and chemosynthetic biota in mounded bathymetry at mid-slope hydrocarbon seeps: Northern Gulf of Mexico. Marine Geology 198, 133-58.

McConnell, D.R., Kendall, B.A., 2003. Images of the base of gas hydrate stability in the deepwater Gulf of Mexico: Examples of gas hydrate traps in northwest Walker Ridge and implications for successful well planning. The Leading Edge April, 361-67.

Milkov, A.V., Sassen, R., 2001. Estimate of gas hydrate resource, northwestern Gulf of Mexico continental slope. Marine Geology 179, 71-83.

Nelson, T.H., 1991. Salt tectonics and listric-normal faulting. In: Salvador, A., (Ed.), The Gulf of Mexico Basin. The Geology of North America vol. J, The Geological Society of America. Boulder, Colorado, pp. 73- 89.

Reilly, J.F., MacDonald, I.R., Biegert, E.K., Brooks, J.M. ,1996. Geologic controls on the distribution of chemosynthetic communities in the Gulf of Mexico. In: Schumacher, D., Abrams, M.A., (Eds.), Hydrocarbon Migration and Its Near-Surface Expression: AAPG Memoir 66, pp.39-62.

Salvador, A., 1991. Triassic-Jurassic. In: Salvador, A., (Ed.), The Gulf of Mexico Basin. The Geology of North America vol. J, The Geological Society of America. Boulder, Colorado, pp. 131-180.

Sassen, R., Cole, G.A., Drozd, R., Roberts, H.H., 1994. Oligocene to holocene hydrocarbon migration and salt-dome carbonates, northern Gulf of Mexico. Marine and Petroleum Geology 11.1, 55-65.

Sawyer, D. S., Buffler, R.T., Pilger, R.H., Jr., 1991. The crust under the Gulf of Mexico basin. In: Salvador, A., (Ed.), The Gulf of Mexico Basin. The Geology of North America vol. J, The Geological Society of America. Boulder, Colorado, pp. 53-72.

Shedd, B., Godfriaux, P., Frye M., Boswell, R., Hutchinson, D., 2009. Occurrence and variety in seismic expression of the base of gas hydrate stability in the Gulf of Mexico, USA. Fire in the Ice Methane Hydrate Newsletter Winter, 11-14.

Shipley, Thomas H., Richard T. Buffler, and Joel S. Watkins. Seismic stratigraphy and geologic history of Blake Plateau and adjacent Western Atlantic Continental Margin. AAPG Bulletin 6.5 (1978): 792-812. Print.

Sohl, N.F., Martinez R., E., Salmeron-Urena, P., Soto-Jaramillo, F., 1991. Upper cretaceous. In: Salvador, A., (Ed.), The Gulf of Mexico Basin. The Geology of North America vol. J, The Geological Society of America. Boulder, Colorado, pp. 205-244.

Watkins, J.S., MacRae, G., Simmons, G.R., 1995. Bipolar simple-shear rifting responsible for distribution of mega-salt basins in Gulf of Mexico? In: C.J. Travis (Ed.), Salt, Sediment and Hydrocarbons: Gulf Coast Section SEPM Sixteenth Annual Research Conference 1995, pp. 297-305.

Watkins, J.S., Bryant, W.R., Buffler, R.T., 1996. Structural Framework Map of the Northern Gulf of Mexico. In: Jones, J.O., Freed, R.L., (Eds.), Structural Framework of the Northern Gulf of Mexico. Special publication. Gulf Coast Association of Geological Societies, 1996, pp. 95-98.

Worrall, D.M., Snelson, S., 1989. Evolution of the northern Gulf of Mexico, with emphasis on Cenozoic growth faulting and the role of salt. In Bally, A.W., Palmer, A.R., (Eds.), The Geology of North America-An overview. The Geology of North America, vol. A, The Geological Society of America. Boulder, Colorado, pp. 97-138.

APPENDIX A

FIGURES

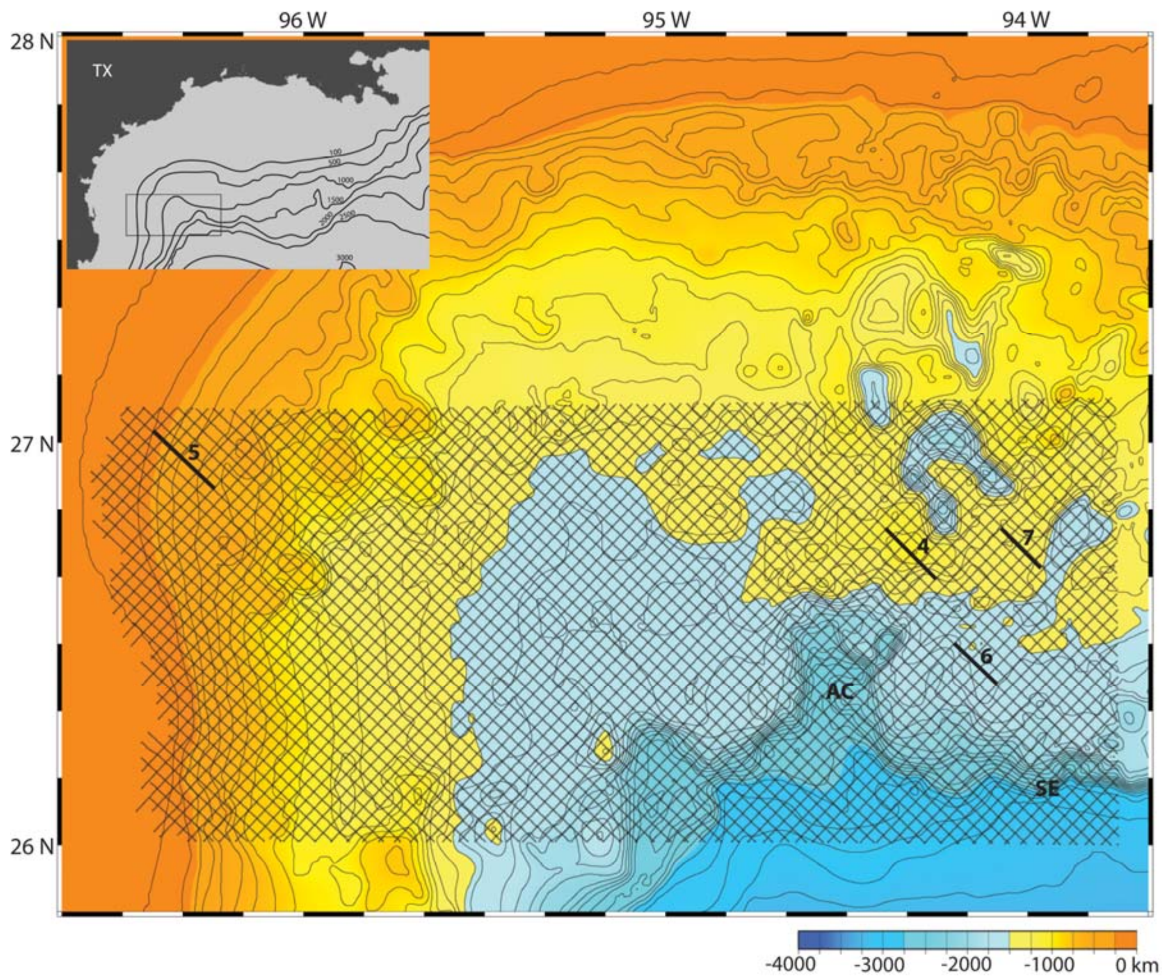

Figure 1: Location, Bathymetry and Seismic Grid
The seismic grid is overlain in black lines, with highlighted portions corresponding to other figures. The bathymetry has a contour interval of 250 m and is predicted from satellite altimetry (Smith and Sandwell, 1997). The inset shows the location of the study area, highlighted in the rectangle, with the regional setting of the Texas coast. AC (Alaminos Canyon), and SE (Sigsbee Escarpment) denote basin features detailed in the text.

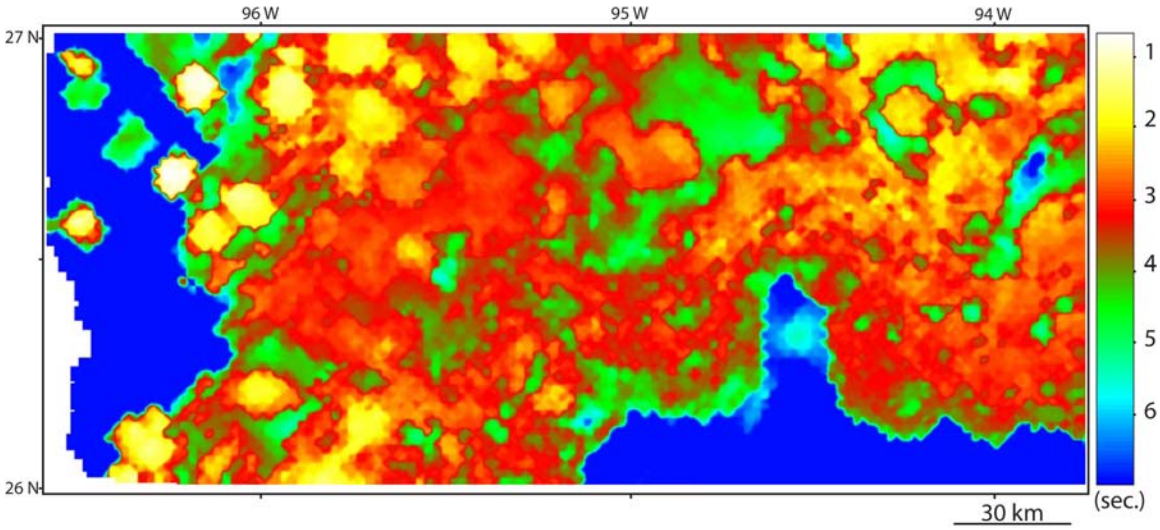

Figure 2: Top of Salt

Surface topography of the top of the salt in seconds (twtt). Isolated salt bodies can be seen in the western region while the salt is more massive and continuous in the eastern region.

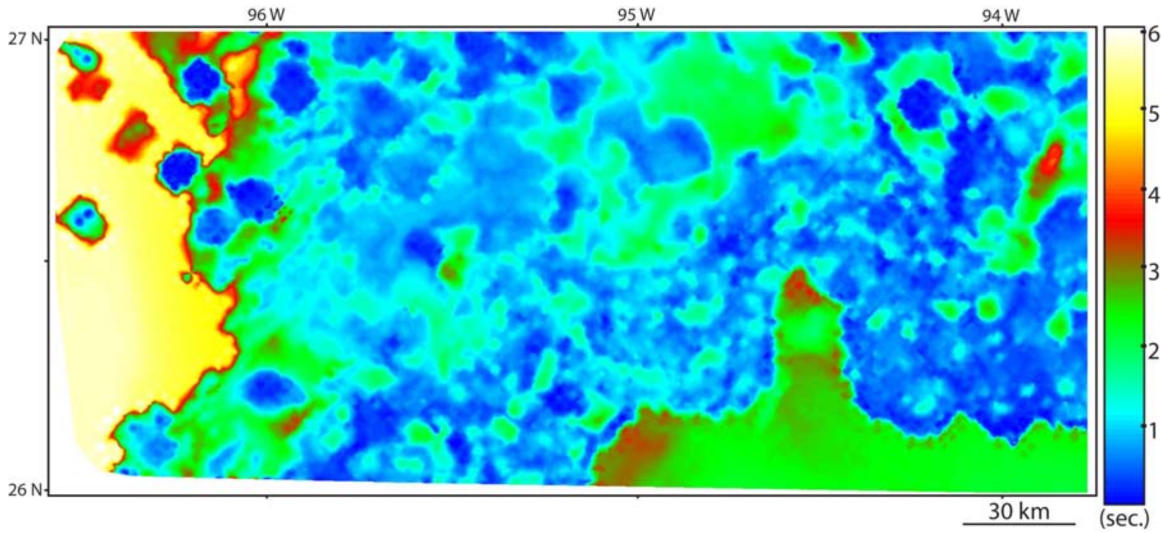

Figure 3: Isopach of Sediment over Salt

The isopach shows the thickness of the sediment between the top of the salt and the seafloor in seconds (twtt). The western portion of the region has the thickest sediment section, while there is a thinner sediment section in the eastern region above the more continuous salt body.

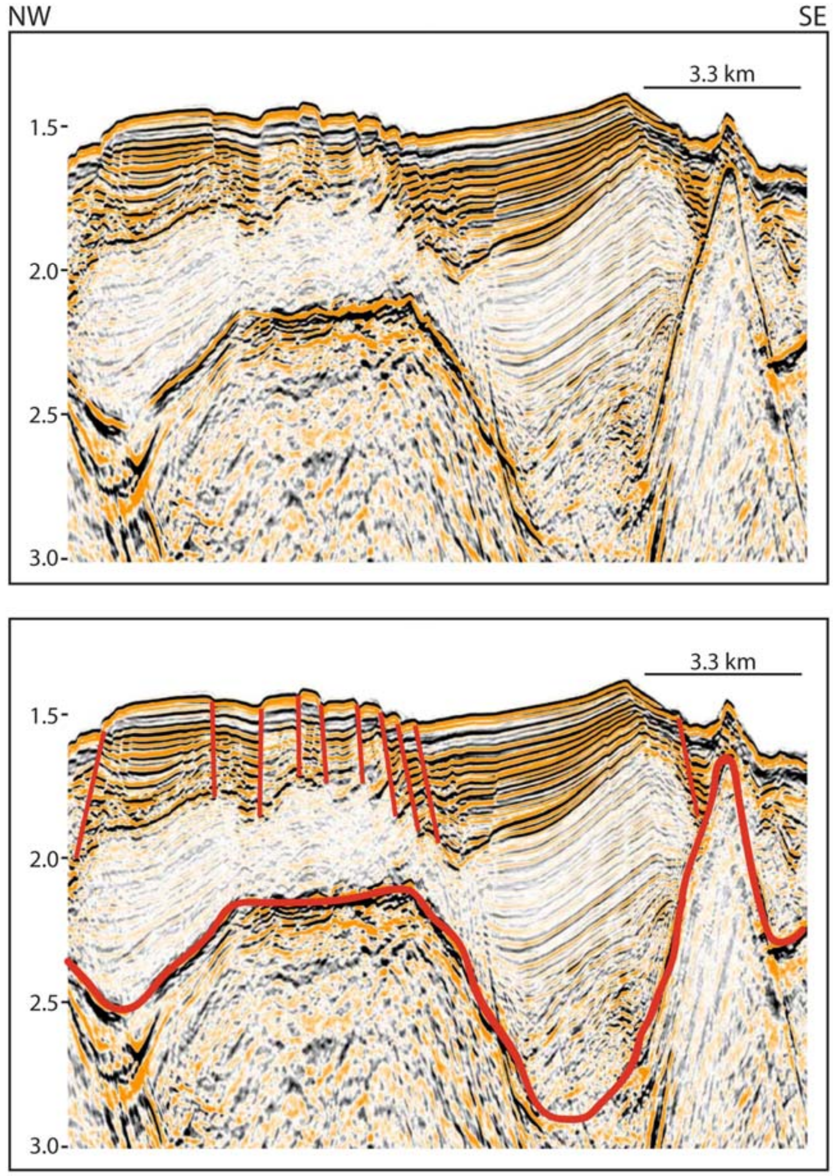

Figure 4: Eastern Region Faults: Local Salt Tectonic Faults

These faults are found in the eastern region and are indicative of the faulting style of the region. The faults are the result of salt tectonism and are located in the thin sediment section above the top of salt. Faults and the top of salt are interpreted at the bottom of the figure. The vertical axis is in seconds of twtt.

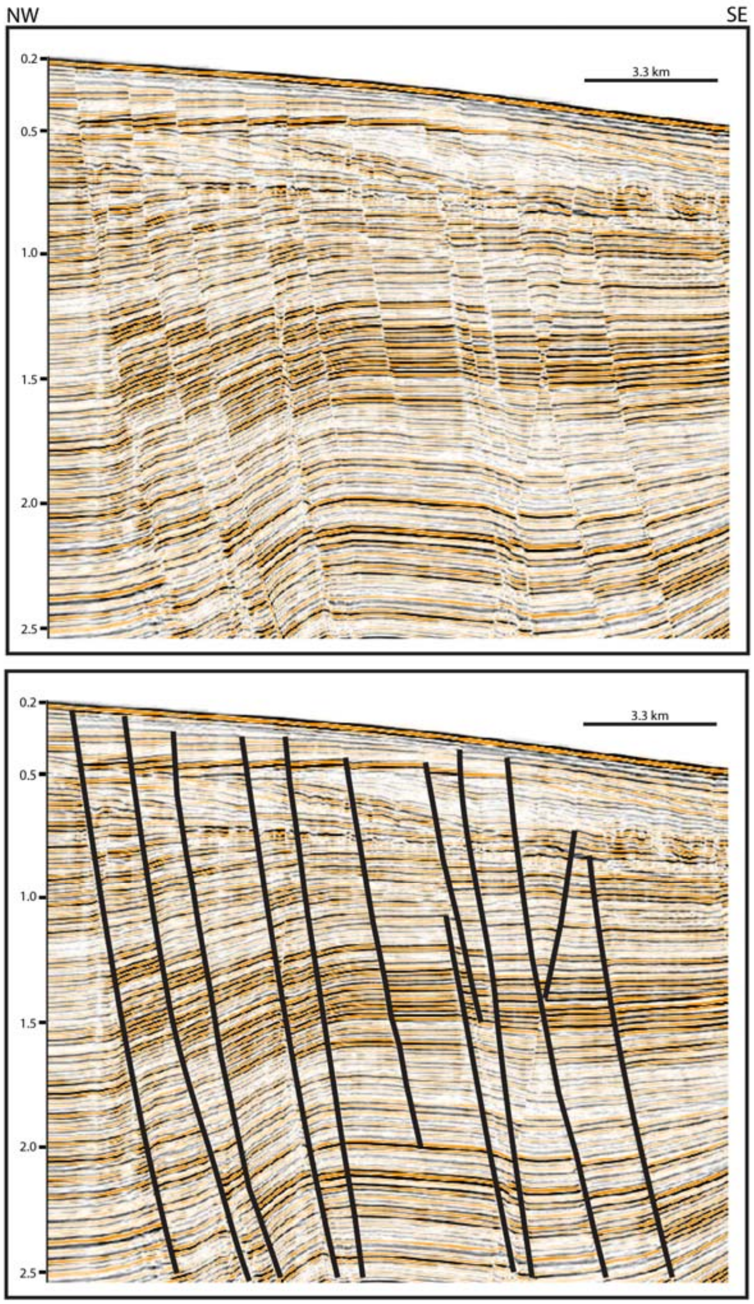

Figure 5: Western Region Faults: Long, Linear Faults

These faults are found in the western region and are indicative of the faulting style of the region. The long, linear, listric faults are parallel to slope and are the result of gravitational extension. Faults are interpreted at the bottom of the figure. The vertical axis is in seconds of twtt.

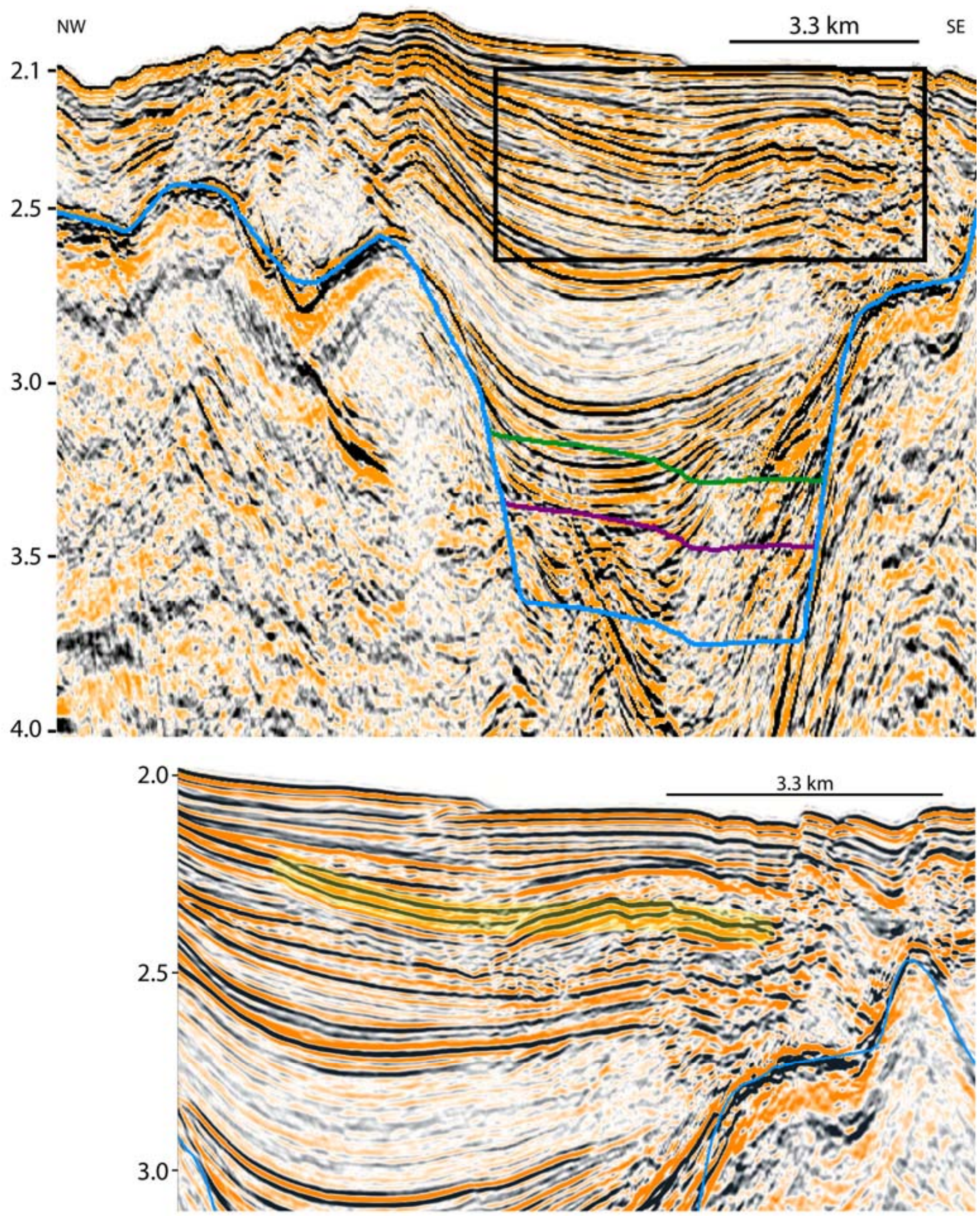

Figure 6: Continuous BSR and GHSZ

The GHSZ is represented by the green, purple, and blue lines. Each color represents the GHSZ for a different concentration of methane, with the green = 100% CH_4, purple = 95.9% CH_4, and blue = 90.4% CH_4. The close up of the boxed region shows a BSR highlighted in yellow. This is an example of a 'continuous BSR' as per the new BSR definitions. The vertical axis is in seconds of twtt.

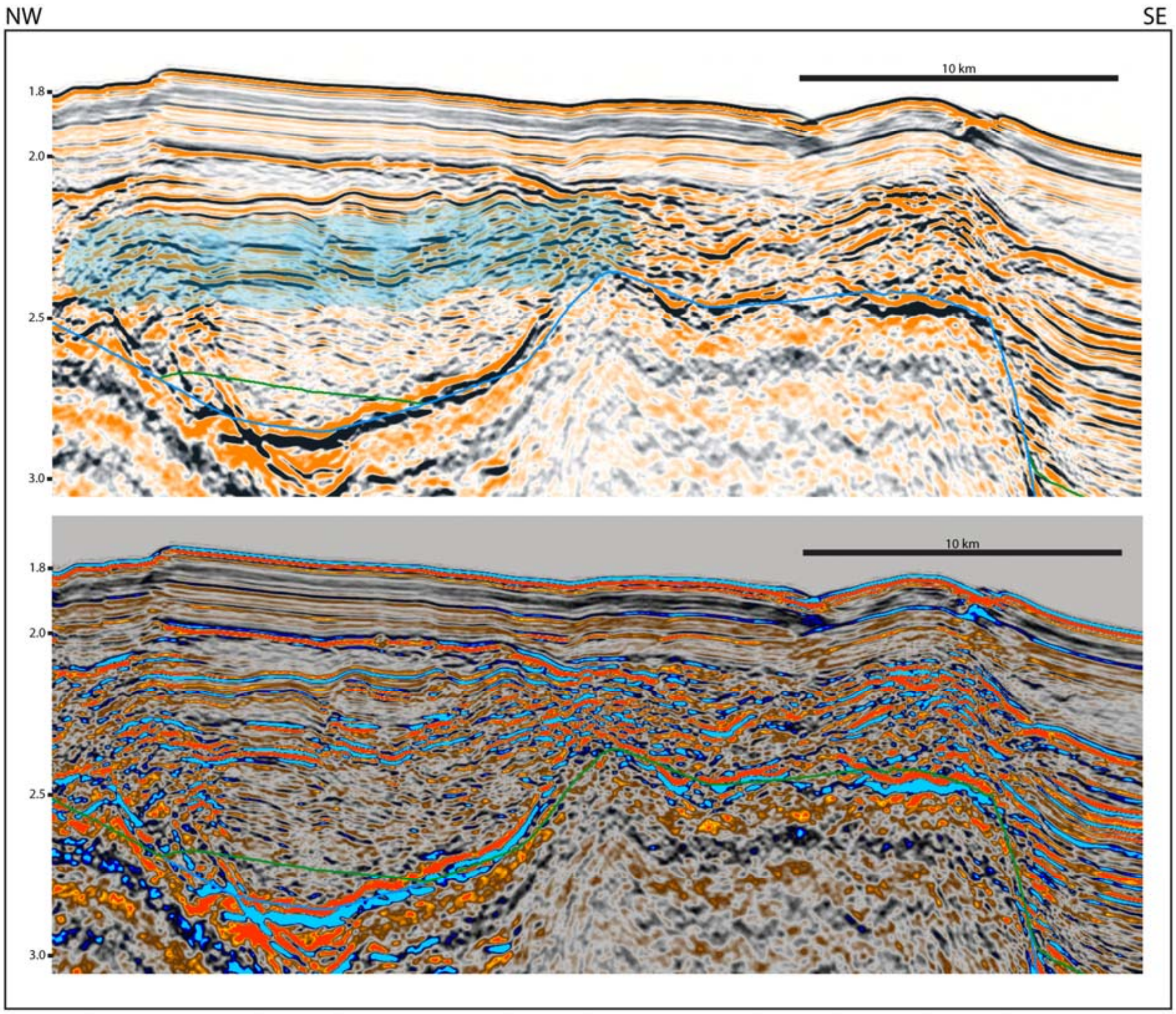

Figure 7: Segmented BSR

The GHSZ is represented by the blue and green lines. The green line is the GHSZ for 100% CH_4. The blue line is the top of the salt. A 'segmented BSR' is highlighted in blue in the upper portion of the figure. The lower portion shows the same seismic section with a different color scale to better highlight the segmented BSR. The vertical axis is in seconds of twtt.

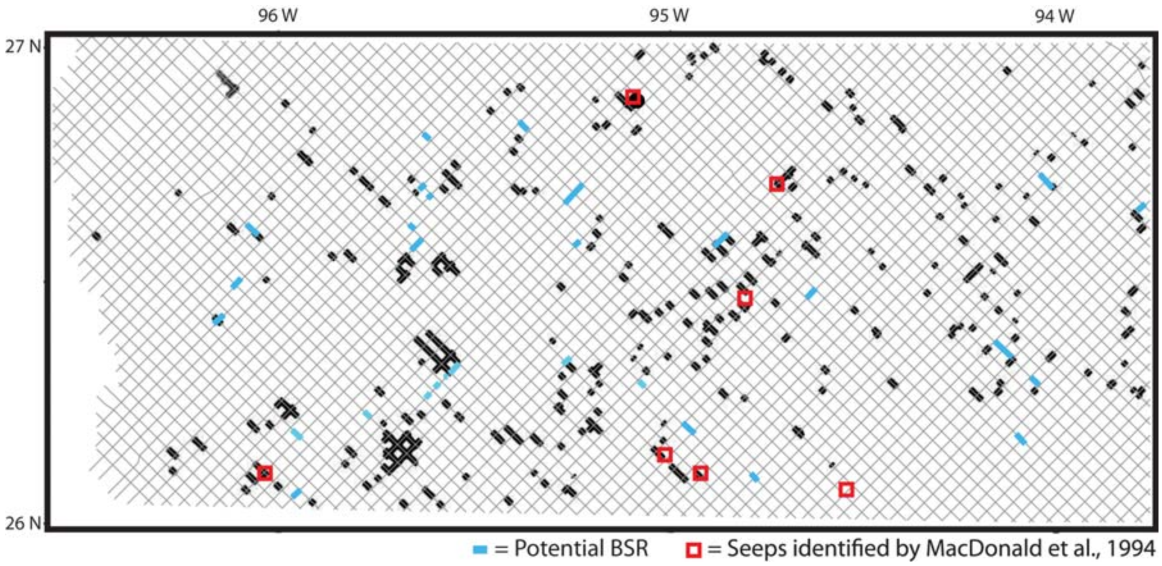

Figure 8: Location of Seeps and Potential BSRs

Seep locations found in the seismic data are shown in black. Seep locations identified by MacDonald et al., 1994 are shown with red boxes. Potential BSRs are shown in blue.

VITA

Name:	Leslie Ann Nemazi
Address:	The Department of Oceanography, Texas A&M University, College Station, TX, 77843-3146
Email Address:	nemazil@gmail.com

Education:	B.S., Geology, The University of Michigan, 2007 M.S., Oceanography, Texas A&M University, 2010